Cherenkov Telescope Array Prospects for New Physics and Millisecond Pulsars at the Galactic Center

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GRAPPA (Amsterdam U.)

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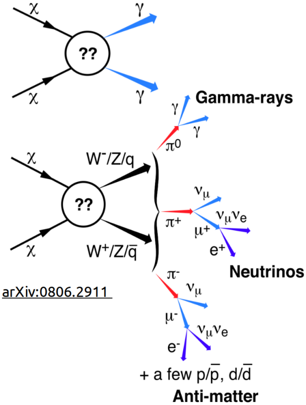
GRavitation AstroParticle Physics Amsterdam

Outline

1. Introduction
2. Galactic Center Anomalies
3. Dark matter searches with H.E.S.S. and MAGIC in the Galactic Center
4. CTA Sensitivity to WIMP particles
5. CTA Sensitivity to a population of millisecond pulsars

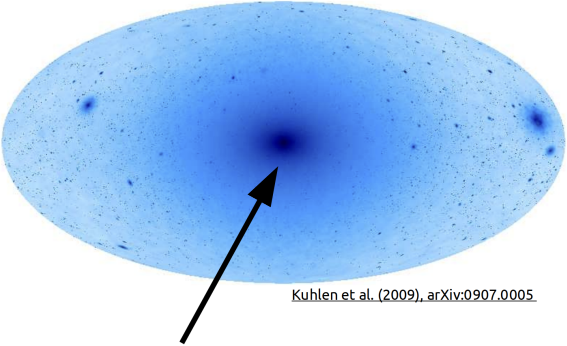
Introduction

Searches for DM emission in the Galactic Center



arXiv:0806.2911

$$\propto \int_{l.o.s} dl \; \rho^2_{\rm DM}$$



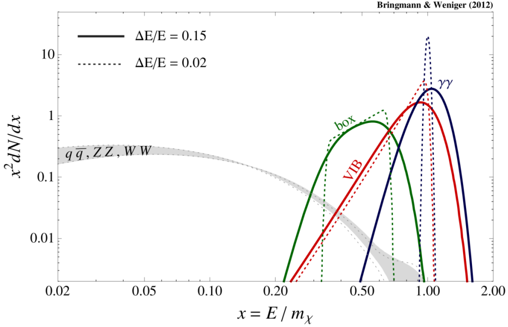
Kuhlen et al. (2009), arXiv:0907.0005

Gamma rays are a very powerful way to probe heavy DM candidates

The largest intensity of DM emission in the Universe

Predicted Spectra for various Dark Matter Models

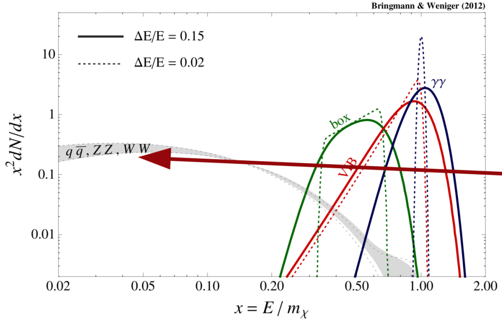
box: e.g., Ibarra et al. (arXiv:1205.0007)
VIB: e.g., Garcia-Cely et al.(arXiv:1512.02801)



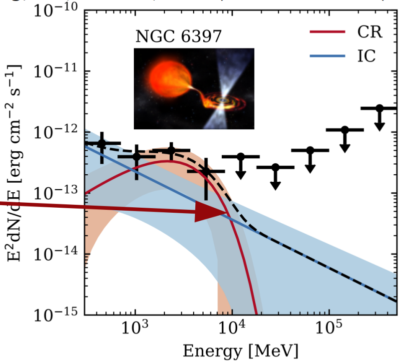
Predicted gamma-ray spectra for different dark matter candidates

The Characteristic Spectra of Background Sources

box: e.g., Ibarra et al. (arXiv:1205.0007)
VIB: e.g., Garcia-Cely et al.(arXiv:1512.02801)



Song, **OM**, Horiuchi, et. al. (arXiv:2102.00061)



Continuous gamma rays from dark matter are degenerate with the astrophysical background (e.g., emission from millisecond pulsars)

Galactic Center Anomalies

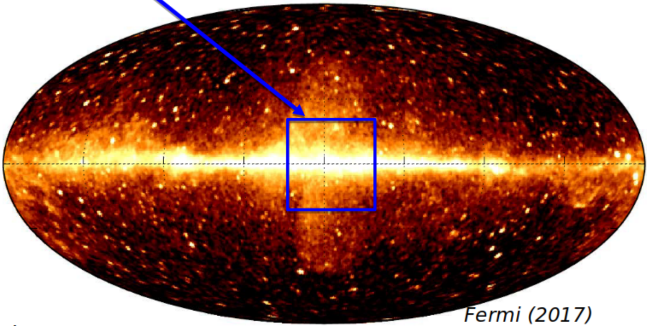
The Galactic Gamma Ray Center Excess

From the Galactic Center out to mid-latitudes

Goodenough & Hooper (2009)
Vitale & Morselli, Phys.Lett.B (2009)
Hooper & Goodenough, PRD (2011)
Hooper & Linden, PRD (2011)
Boyarsky et al. PRD (2011)
Abazajian & Kaplinghat, PRD (2012)
Gordon & Macias, PRD (2013)
Hooper & Slatyer PRD (2013)
Huang et al. PRD (2013)
Macias & Gordon, PRD (2014)
Abazajian et al. PRD (2014, 2015)
Calore et al. JCAP (2014)
Zhou et al. PRD (2014)
Daylan et al. PRD (2014)
Macias et al. MNRAS (2016)
Selig et al. JCAP (2015)
Huang et al. PRD (2015)
Gaggero et al. PRD (2015)
Carlson et al. PRD (2015, 2016)
Yang & Aharonian, A&A (2016)
Horiuchi et al. JCAP (2016)
Lee et al. PRL (2016)
Linden et al. PRD (2016)
Ackermann et al. ApJ (2017)
Ajello et al. ApJ (2017)
Macias et al. Nat. Astr. (2018)
Bartels et al. Nat. Astr. (2018)
Macias et al. JCAP (2019)
Abazajian et al. (2020)
... (not a complete list)

Method

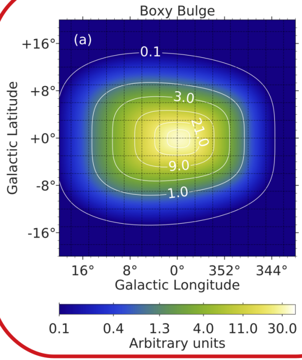
Found by morphological template fitting



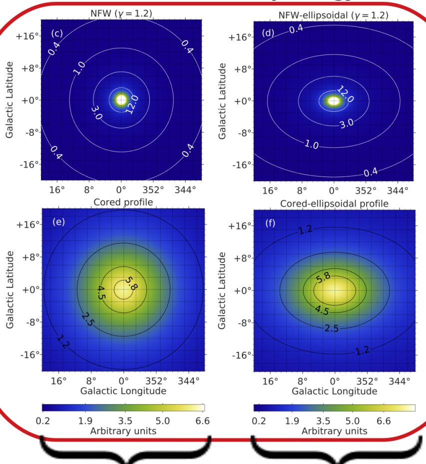
Fermi (2017)

The spatial morphology of Dark Matter versus Stellar Mass

Millisecond Pulsars distribution



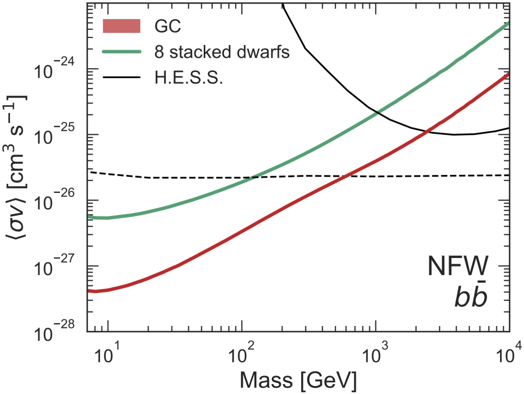
Dark Matter morphology



Spherical **Ellipsoidal**

Abazajian, Horiuchi, Kaplinghat, Keeley, **OM**, PRD (2020), arXiv:2003.10416

Constraints using Galactic Center gamma-ray observations

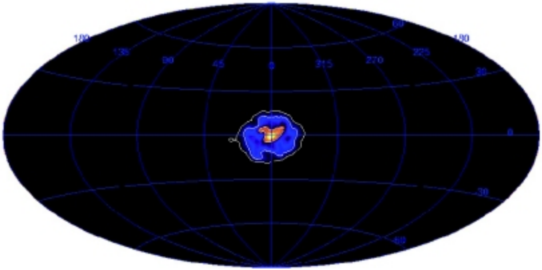


Abazajian, Horiuchi, Kaplinghat, Keeley, **OM**, PRD (2020), arXiv:2003.10416

Summary:

- Accounted for uncertainties in the astrophysical background model.
- Considered the uncertainties in the dark matter profile parameters.
- Thermal dark matter particles ruled out for $m_{\rm dm} \leq 400$ GeV.

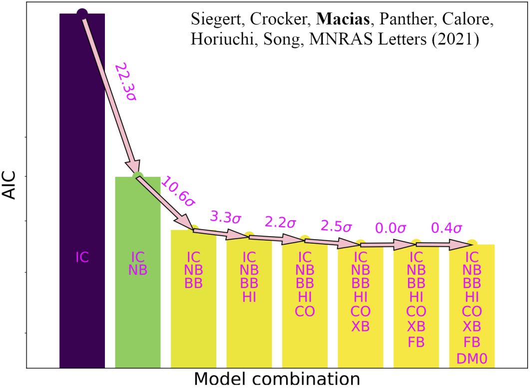
The 511 keV Line Excess at the Galactic Center



Knodlseder et al., A&A (2005)

- Bulge/Disk flux ratio ~ 1 [Siegert et al. (2016)]
- Guaranteed contribution from thermonuclear supernovae (^{56}Co, ^{44}Ti)
- Sgr A* [Totani 2006], pulsars [Wang+2006], X-ray binaries [Guessoum+2006], neutron star mergers [Fuller+2018], or dark matter [Boehm+(2004)].

The 511 keV Line Excess at the Galactic Center



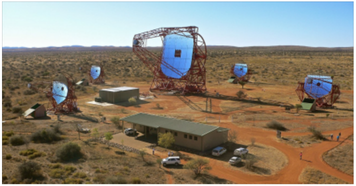
IC:=inverse Compton, NB:=Nuclear bulge, BB:=Boxy bulge, HI:=hydrogen gas, FB:=Fermi bubbles, DM:= dark matter.

Main Results:

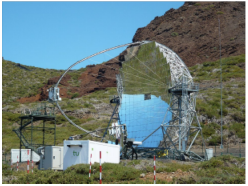
- The spatial morphology of the 511 keV signal is correlated with stellar mass in the Galactic bulge.
- Once stellar templates are included in the model, there is no longer need for a dark matter template.

Dark matter searches with H.E.S.S. and MAGIC in the Galactic Center

Imaging Atmospheric Cherenkov Telescopes

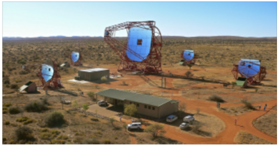


H.E.S.S.
1) Energy range > 30 GeV
2) Angular resolution ~0.03 degrees
3) Field of view ~ 5 degrees

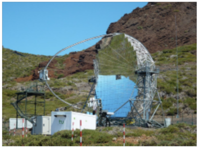


MAGIC
1) Energy range > 50 GeV
2) Angular resolution ~0.08 degrees
3) Field of view ~ 3.5 degrees

Dark matter search campaigns with H.E.S.S. and MAGIC



H.E.S.S.
1) Energy range > 30 GeV
2) Angular resolution ~0.03 degrees
3) Field of view ~ 5 degrees

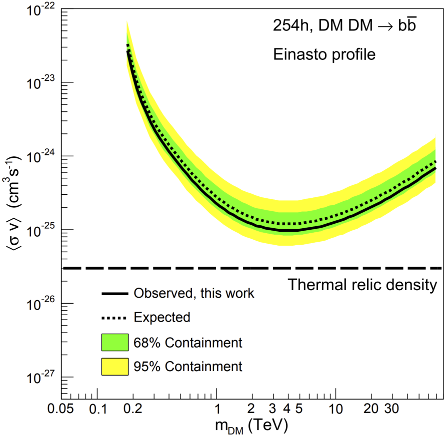


MAGIC
1) Energy range > 50 GeV
2) Angular resolution ~0.08 degrees
3) Field of view ~ 3.5 degrees

Doro et al (2021)

Target	Year	Time [h]	IACT	Limit	Ref.
The Milky Way central region & halo					
MW Centre	2004	(48.7)	H.E.S.S.	Ann.	Aharonian et al. (2006)
MW Inner Halo	2004 – 2008	(112)	H.E.S.S.	Ann.	Abramowski et al. (2011)
	2010	9.1		Ann.	Abramowski et al. (2015)
	2004 – 2014	254		Ann.	Abdallah et al. (2016)
	2014 – 2020	546	H.E.S.S.†	Ann.	Montanari et al. (2021)
MW Outer Halo	2018	10	MAGIC	Decay	Ninci et al. (2019)

H.E.S.S. Searches for Continuous Dark Matter Emission



Abdallah et al., PRL (2016) [H.E.S.S. Coll.]

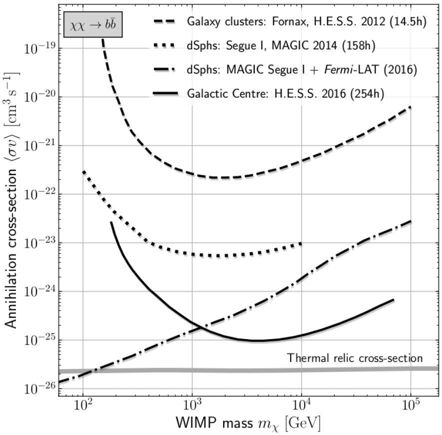
Summary:

- Analyzed the inner 300 pc of the Galactic Center.
- Data collected over a 10 yrs period (2004-2014).
- Used an Einasto profile

$$\rho_{\mathrm{E}}(r) = \rho_{\mathrm{s}} \exp\left[-\frac{2}{\alpha_{\mathrm{s}}}\left(\left(\frac{r}{r_{\mathrm{s}}}\right)^{\alpha_{\mathrm{s}}} - 1\right)\right]$$

where $\alpha_s = 0.17$, $r_s = 20$ pc, and $\rho_\odot = 0.3$ GeV cm^{-3}.

H.E.S.S. vs MAGIC (Continuous Emission)

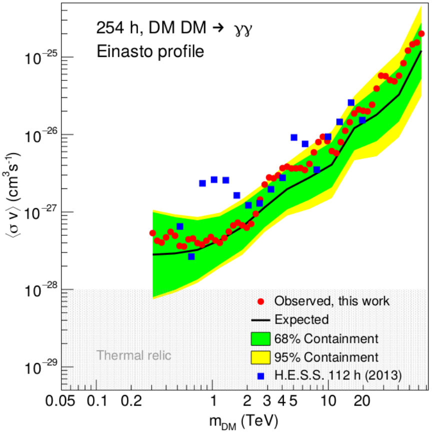


Doro et al., (2021)

Summary:

- Strongest constraints come from Galactic Center observations.
- All analyses assume a Navarro-Frenk-White profile.
- Fermi LAT limits dominate for dark matter masses smaller than ~ 1 TeV.

H.E.S.S. searches for gamma-ray lines in the Galactic Center



Abdalla et al., (2018) [H.E.S.S. Coll.]

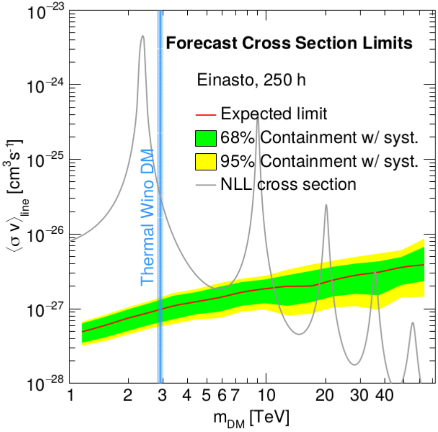
Summary:

- Model independent limits on a line-like dark matter signal.
- Data collected over a 10 yrs period.
- Adopted Einasto profile

$$\rho_{\rm E}(r) = \rho_{\rm s} \exp\left[-\frac{2}{\alpha_{\rm s}}\left(\left(\frac{r}{r_{\rm s}}\right)^{\alpha_{\rm s}} - 1\right)\right]$$

where $\alpha_s = 0.17$, $r_s = 20$ pc, and $\rho_\odot = 0.3$ GeV cm^{-3}.

H.E.S.S. Sensitivity to a realistic Wino dark matter signal



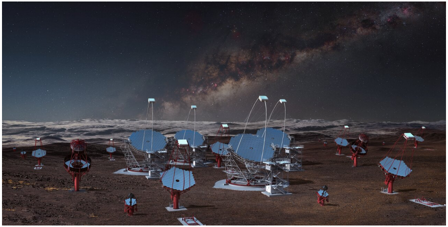
Rinchuso et al., PRD (2018)

Summary:

- Considered precision Wino photon spectrum.
- Used mock H.E.S.S. observations of the inner 4° of the Galactic center.
- Using the full spectral shape of the Wino leads to an improved sensitivity.

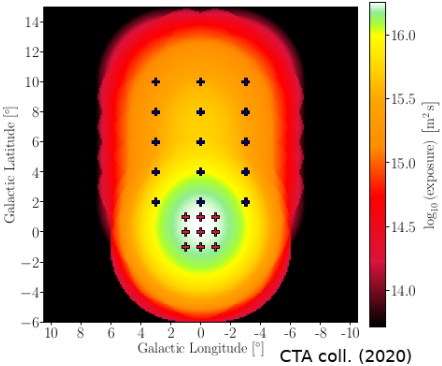
CTA Sensitivity to WIMP particles

Galactic Center Observation Strategy for CTA



Cherenkov Telescope Array:

- Beginning of observations in 2025.
- Energy resolution ≈ 10 GeV to 300 TeV.
- Angular resolution 0.2 to 0.02 deg.
- Southern site more sensitive to the Galactic Center.

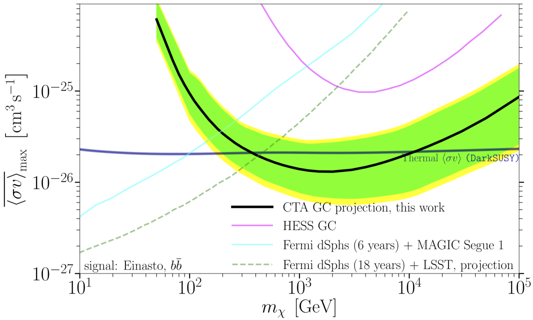


CTA coll. (2020)

CTA observation strategy

- Multiple pointing observations of the Galactic Center.
- Diffuse observations achievable by stitching images together.

CTA Sensitivity to Continuous Dark Matter Emission



Acharyya et al., JCAP (2021) [CTA Coll.]

Summary:

- Considered 525 h observations of the inner $10^\circ \times 10^\circ$ region.
- Included systematic uncertainties in the astrophysical backgrounds.
- Used an Einasto profile with $\alpha_s = 0.17$, $r_s = 20$ pc, and $\rho_s = 0.089$ GeV cm^{-3}.

CTA Sensitivity to Wino Dark Matter

PHYSICAL REVIEW D **103,** 023011 (2021)

Prospects for detecting heavy WIMP dark matter with the Cherenkov Telescope Array: The Wino and Higgsino

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(Received 30 July 2020; accepted 8 December 2020; published 12 January 2021)

TeV-scale particles that couple to the standard model through the weak force represent a compelling class of dark matter candidates. The search for such weakly interacting massive particles has already spanned ...ultiple decades, and whilst it has yet to provide any definitive evidence for their existence, viable ...r space remains. In this paper, we show that the upcoming Cherenkov Telescope Array (CTA) ...ensitivity to uncharted parameter space at the TeV mass scale. To do so, we focus on two ...ter candidates, the Wino and Higgsino. Sensitivity forecasts for both models are ...ducible background from misidentified cosmic rays, as well as a range of ... at TeV energies. For each candidate, we find substantial expected ...urrent imaging atmospheric Cherenkov telescopes. In detail, for ...oughly an order of magnitude in $\langle\sigma v\rangle$, whereas for the ...become the first experiment that has sensitivity to ...ities demonstrate the discovery potential for ...

Computation of the γ-ray spectra and annihilation rate

Wino dark matter:

- Sommerfeld enhancement. [Hisano et al.(2004)]
- Continuum emission of photons from the decay of final state W and Z bosons. [Cirelli et al. (2010)]
- Sudakov double logarithms of the form $\alpha_W \ln^2(m_{\rm DM}/m_W)$ [Hryczuk et al. (2011)].
- Inclusion of endpoint photons, which have $E = zm_{\rm DM}$ with $1 - z \ll 1$. [Baumgart et al. (2015)].

Used full next-to-leading logarithmic (NLL) accuracy in the spectrum.

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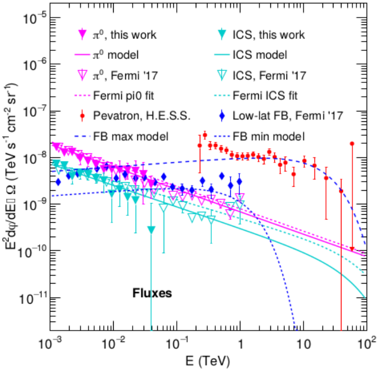
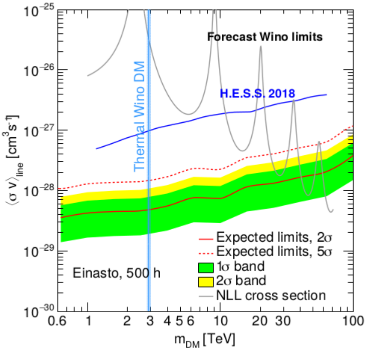
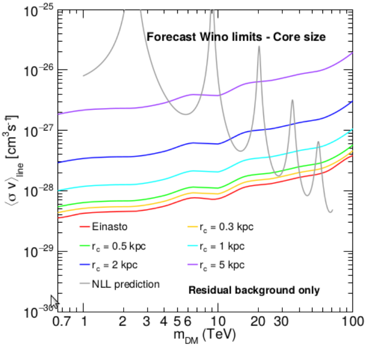


Astrophysical background:

- Model 1: simulated using GALPROP V56.
- Model 2: extrapolation of Fermi background model.

Expected 95% C.L. upper limits on $\langle \sigma v \rangle_{\mathrm{line}}$: Wino dark matter





Wino sensitivity:

- CTA will have the best sensitivity to the thermal Wino dark matter.
- Uncertainties in the dark matter profile parameters provide the biggest source of uncertainties.

[*] Assumed $\frac{dN_\gamma}{dE} = 2\delta(E - m_{\mathrm{DM}}) + \frac{dN_\gamma^{\mathrm{ep}}}{dE} + \frac{dN_\gamma^{\mathrm{ct}}}{dE}$, and $\langle \sigma v \rangle_{\mathrm{line}} = \langle \sigma v \rangle_{\gamma\gamma + \gamma Z/2}$

CTA Sensitivity to a population of millisecond pulsars

CTA Sensitivity to the High Energy Tail of the Galactic Center Excess

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Advance Access publication 2021 May 21
https://doi.org/10.1093/mnras/stab1450

Cherenkov Telescope Array sensitivity to the putative millisecond pulsar population responsible for the Galactic Centre excess

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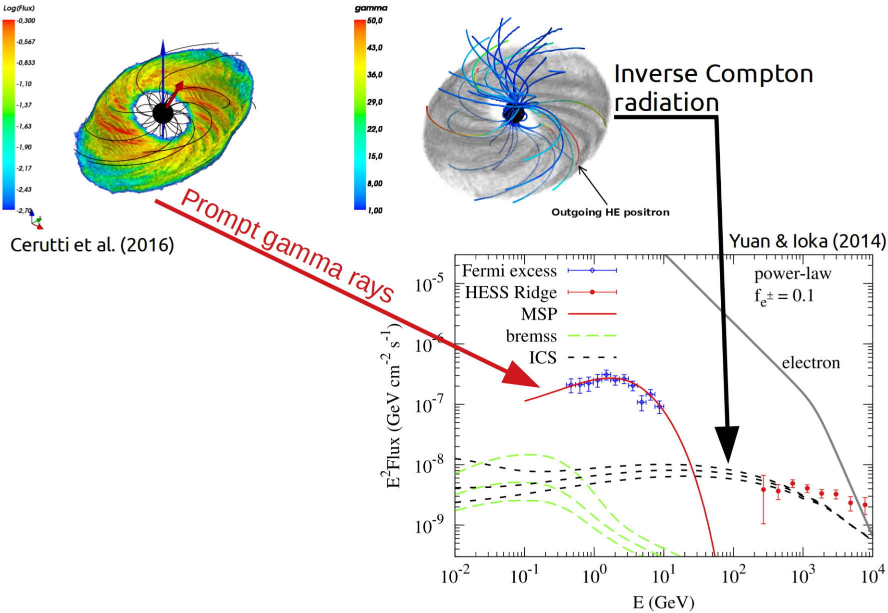
... of the *Fermi* Galactic Centre γ-ray excess is the extended emission from an unresolved population ... (MSPs) in the Galactic bulge. Such a population would, along with the prompt γ-rays, also inject large ... $(e^{\pm})$ into the interstellar medium. These $e^{\pm}$ could potentially inverse-Compton (IC) scatter ... within the sensitivity range of the upcoming Cherenkov Telescope Array (CTA). In this ... CTA to this signature by making a realistic estimation of the systematic uncertainties ... γ-ray energies. We forecast that, in the event that $e^{\pm}$ injection spectra are ... over the IC signature of a putative Galactic bulge MSP population ... efficiencies in the range of $\approx$2.9–74.1 per cent, or higher, ... components. On the other hand, for spectra softer than ... efficiency of $\gtrsim$158 per cent. However, even ... and/or modelling uncertainties can be ... fully discriminate between an MSP ...

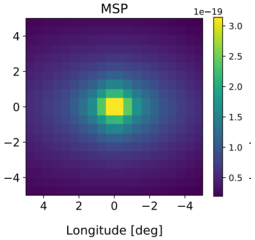
Millisecond pulsar emission at the ∼ GeV–TeV energy scale



Cerutti et al. (2016)

Yuan & Ioka (2014)

Simulation of the Millisecond Pulsars inverse Compton signal



Macias et al. (2021)

Model Name	Γ	$E_{\rm cut}$ (TeV)
Baseline	2.0	50
Inj1	1.5	50
Inj2	2.5	50
Inj3	2.0	10
Inj4	2.0	100

The injection spectrum of $e^{\pm}$:

$$\frac{dN_{e^\pm}}{dE} \propto E^{-\Gamma} \exp\left(-\frac{E}{E_{\rm cut}}\right)$$

Injection luminosity:

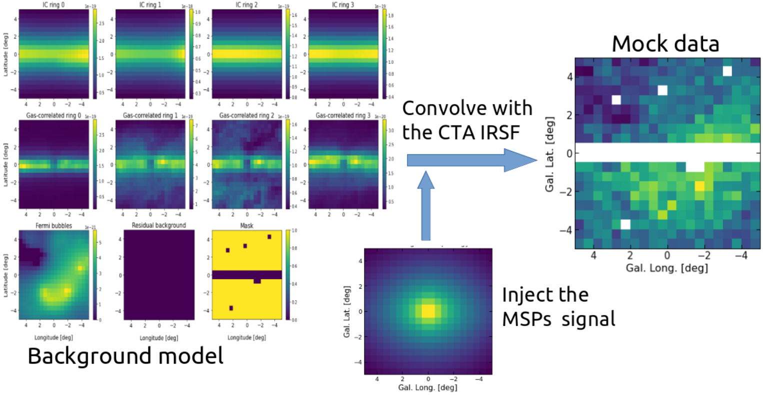
The γ-ray efficiency $f_\gamma \equiv L_{\gamma,\rm prompt}/\dot{E} \simeq 10\%$, with $\dot{E}$ the MSPs spin-down lominosity.

$$\begin{aligned} L_{e^\pm} = f_{e^\pm}\dot{E} &= \frac{f_{e^\pm}}{f_\gamma} L_{\gamma,\rm prompt} \\ &\simeq 10 f_{e^\pm} L_{\gamma,\rm prompt}, \end{aligned}$$

$L^{\rm bulge}_{\gamma,\rm prompt} = (2.2 \pm 0.4) \times 10^{37}$ erg s^{-1} and $L^{\rm NB}_{\gamma,\rm prompt} = (3.9 \pm 0.5) \times 10^{36}$ erg s^{-1}. So, we can finally write:

$$L_{e^\pm} \simeq [(2.7 \pm 0.4) \times 10^{38}] f_{e^\pm} \quad [\rm erg/s]$$

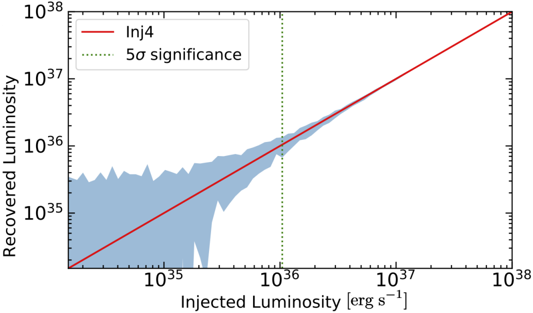
Summary of the Analysis pipeline



Fitting approach:

1. Perfect diffuse emission model: Fit the mock data with the same maps used in the simulations.
2. Mismodeling of the diffuse emission: Fit the mock data with an independent map (not used in the simulations).

Signal Recovery Tests Results



OM, Leijen, Ando, Song, Horiuchi, Crocker, MNRAS (2021)

Model Name	Γ	E_{cut} (TeV)
Baseline	2.0	50
Inj1	1.5	50
Inj2	2.5	50
Inj3	2.0	10
Inj4	2.0	100

$$\frac{dN}{dE_e} \propto E_e^{-\Gamma} \exp(-E_e/E_{cut})$$

Main Results

Model Name	Γ	$E_{\rm cut}$ (TeV)
Baseline	2.0	50
Inj1	1.5	50
Inj2	2.5	50
Inj3	2.0	10
Inj4	2.0	100

Minimum $f_{e^\pm}$ for detection [%]				
Baseline	**Inj1**	**Inj2**	**Inj3**	**Inj4**
Perfect model for the astrophysical background				
10.5%	2.9%	158.4%	24.3%	8.2%
Mismodeling of the astrophysical background				
14.5%	3.8%	163.4%	25.3%	10.8%

$$\frac{dN}{dE_e} \propto E_e^{-\Gamma} \exp(-E_e/E_{\rm cut})$$

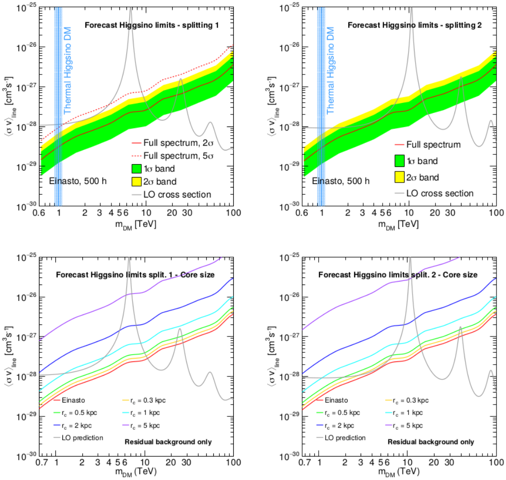
Minimum electron efficiency for a robust CTA detection

For physically plausible electron injection spectra, the prospects for a 5σ detection of the signal are very encouraging.

Conclusions

- Galactic Center anomalies are likely explained by processes related to stars in the Galactic bulge.
- CTA will have at least one order of magnitude greater sensitivity to WIMP dark matter particles than previous telescopes.
- CTA will potentially be able to probe the MSPs hypothesis for the Galactic center excess, for physically plausible $f_{e^\pm}$ values.

Expected 95% C.L. upper limits on $\langle \sigma v \rangle_{\mathrm{line}}$: Higgsino DM



Higgsino dark matter:

- Included only leading order (LO) contributions to the annihilation rate and photon spectra.
- However, promising prospects for CTA sensitivity to thermal Higgsinos.
- Uncertainties in the dark matter profile parameters provide the biggest source of uncertainties.

Specifications of the Analysis

Data reduction procudure:

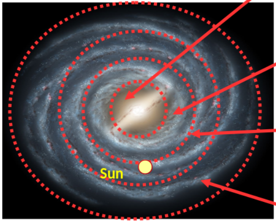
- Size of region of interest: $10^\circ \times 10^\circ$ around the Galactic Center.
- Mask: Galactic plane $|b| \leq 0.3^\circ$, point sources 3FHL catalog, and extended TeV sources.
- Instrument Response Function: `CTA-Performanceprod 3bv1-South-20deg-average-50h.root3`.
- Exposure: 500 hours.
- Energy range: 16 GeV - 158 TeV.
- Spatial bins: $0.5^\circ \times 0.5^\circ$.

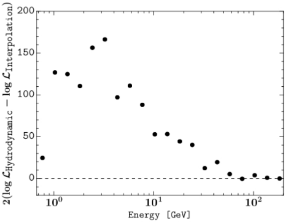
Statistical Analysis:

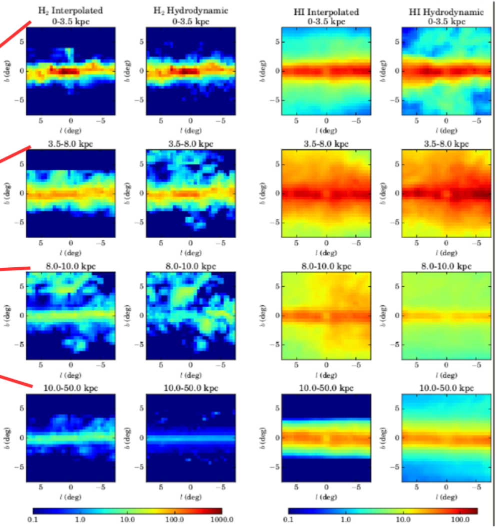
- Spectrum: Binned maximum-likelihood procedure applied to each individual energy bin.
- Morphology: Maps divided in Galactocentric rings.

Astrophysical background: Interstellar gas.

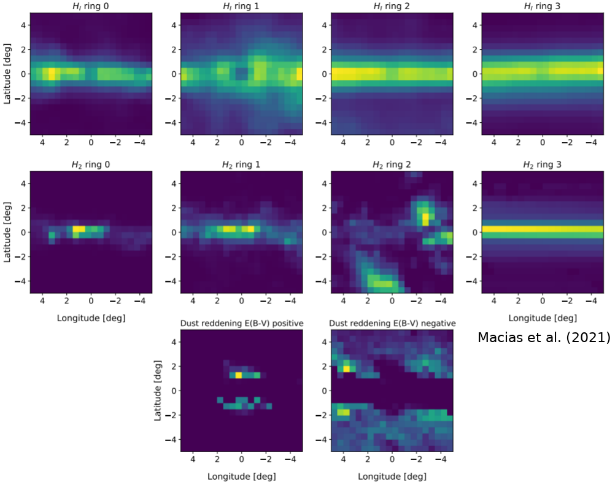
Macias et al. Nat. Astr.(2018)







Astrophysical background: Interstellar gas.

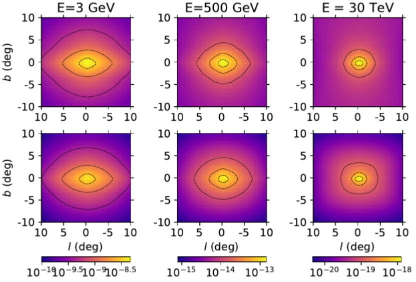


Macias et al. (2021)

Hydrodynamic gas templates:

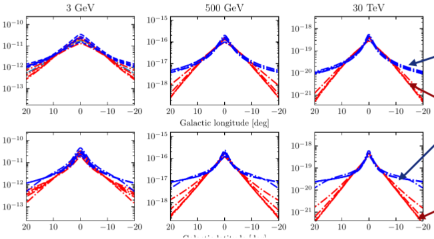
Atomic hydrogen, molecular hydrogen and residual dust templates. These are publicly available on github https://github.com/chrisgordon1/galactic_bulge.

Millisecond Pulsars Vs. dark matter inverse Compton maps



Inverse Compton from dark matter following spherical distribution

Inverse Compton from MSPs following a boxy bulge distribution

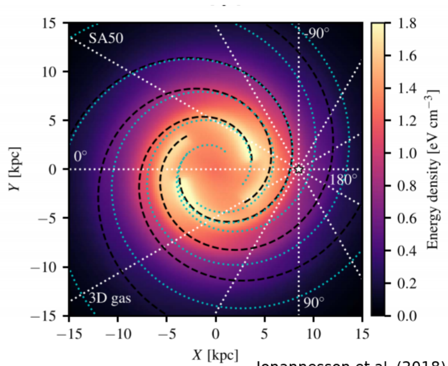


Spherical distribution

Peanut bulge distribution

Song, OM, Horiuchi [PRD 99 (2019) 12, 123020]

Astrophysical background: Alternative model.



Jonannesson et al. (2018)

GALPROP v56 setup:

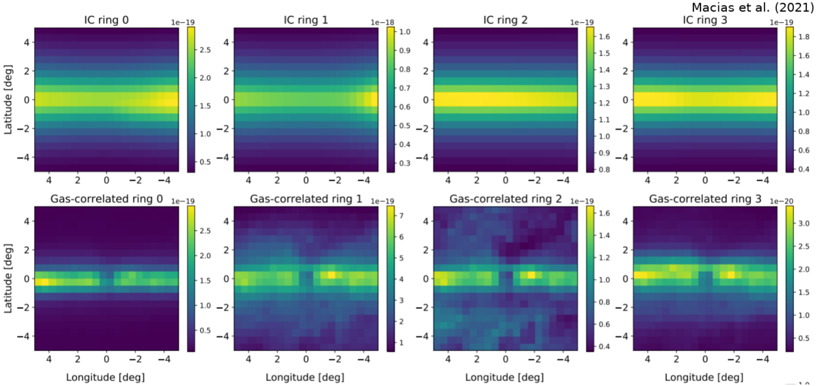
- 3D spatial models for the interstellar radiation fields and interstellar gas.
- Diffusive reacceleration with $\Delta X \Delta Y \Delta Z = 0.2 \times 0.2 \times 0.1$ kpc^3 spatial resolution.

Macias et al. (2021)

Parameter	value
X_h [kpc]	±20.00
Y_h [kpc]	±20.00
Z_h [kpc]	±6.00
ΔX [kpc]	0.2
ΔY [kpc]	0.2
ΔZ [kpc]	0.1
$D_{0,xx}$ [10^{28} cm^{2}s^{-1}]	2.28
δ	0.545
$V_{\rm Alfven}$ [km s^{-1}]	5.26
γ_0	1.51
γ_1	2.35
R_1 [GV]	3.56
$\gamma_{0,H}$	1.71
$\gamma_{1,H}$	2.35
$\gamma_{2,H}$	2.19
$R_{1,H}$ [GV]	4.81
$R_{2,H}$ [GV]	200
$\gamma_{0,e}$	1.81
$\gamma_{1,e}$	2.77
$\gamma_{2,e}$	2.38
$R_{1,e}$ [GV]	5.97
$R_{2,e}$ [GV]	76

This model assumes same power of CR injection in the arms/disk (50% each).

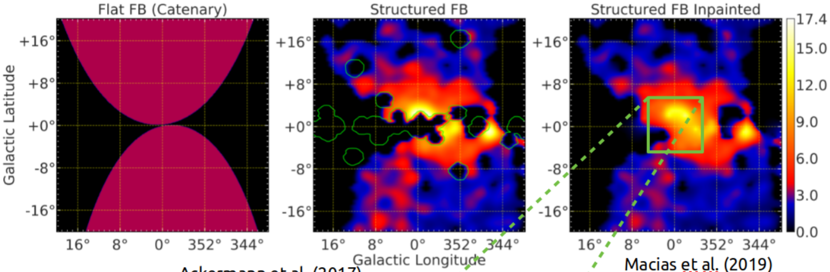
Astrophysical background: simulated γ-ray sky at ≈ 11 TeV



Inverse Compton and gas-correlated maps divided in rings:

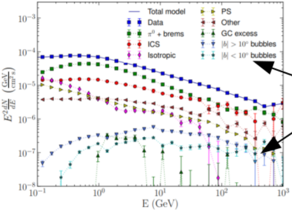
['ring 0','ring 1', 'ring 2', 'ring 3']:=[0 − 3.5, 3.5 − 8.0, 8.0 − 10.0, 10.0 − 50.0] kpc.

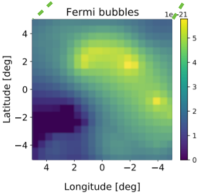
Fermi bubbles model at TeV-scale energy



Macias et al. (2019)

Ackermann et al. (2017)



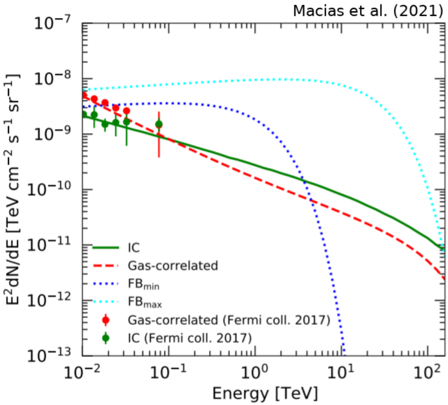


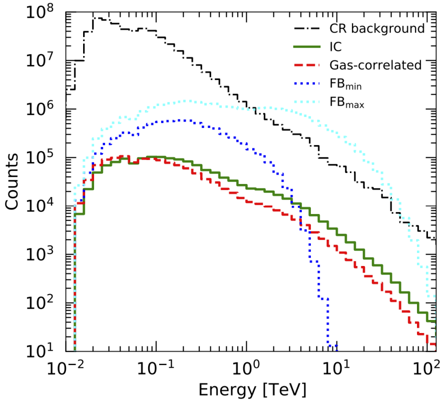
Fermi Bubbles morphology in the inner 10°x10° of the GC.

Method:

Follow the same approach as in Rinchuso et al. (2020) [arXiv: 2008.00692].

Mock data generation for the astrophysical background model





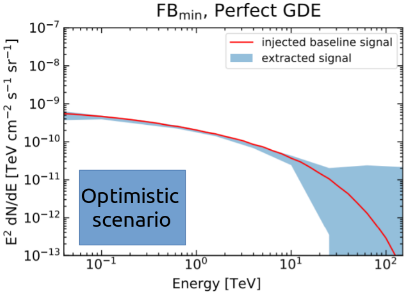
Astrophysical background:

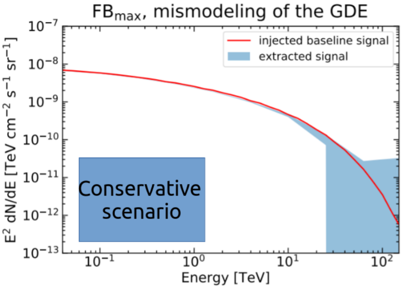
- GDE Model I: simulated using GALPROP V56.
- GDE Model II: extrapolation of hydrodynamic gas models.

CTA expected rate:

- Dominated by irreducible CR background.
- Assumed 500 h of observations.

Results: sensitivity to the putative population of GC MSPs



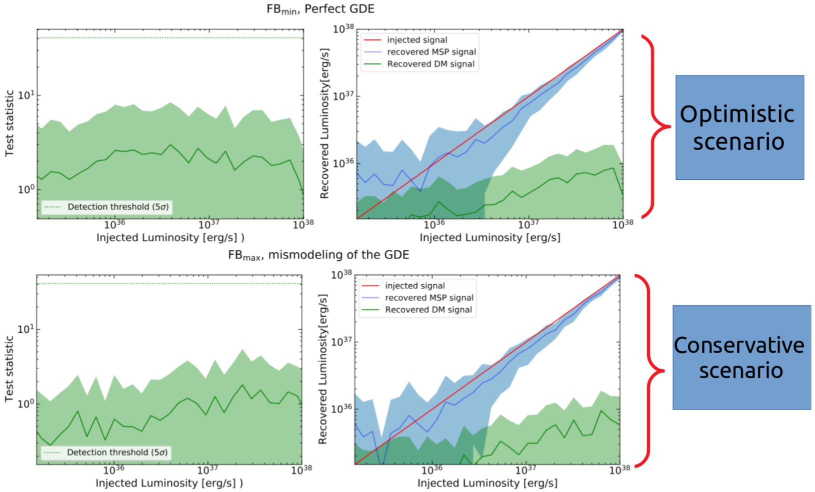


Model Name	Γ	$E_{\rm cut}$ (TeV)
Baseline	2.0	50
Inj1	1.5	50
Inj2	2.5	50
Inj3	2.0	10
Inj4	2.0	100

$$\frac{d^2N}{dE\,dt} \propto E^{-\Gamma} \exp(-E/E_{\rm cut}),$$

Minimum $f_{e^\pm}$ for detection [%]				
Baseline	**Inj1**	**Inj2**	**Inj3**	**Inj4**
$\mathrm{FB_{min}}$, perfect GDE.				
10.5%	2.9%	158.4%	24.3%	8.2%
$\mathrm{FB_{min}}$, mismodeling of the GDE.				
14.5%	3.8%	163.4%	25.3%	10.8%
$\mathrm{FB_{max}}$, perfect GDE.				
57.5%	41.3%	259.4%	55.0%	58.4%
$\mathrm{FB_{max}}$, mismodeling of the GDE.				
72.9%	51.8%	326.7%	70.4%	74.1%

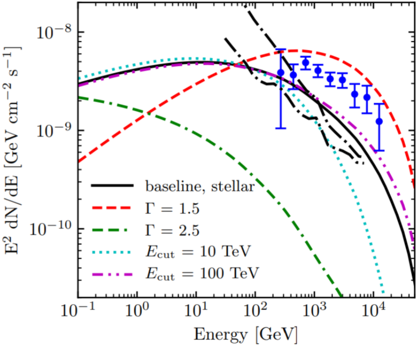
Results: distinguishing MSPs from DM emission in the GC

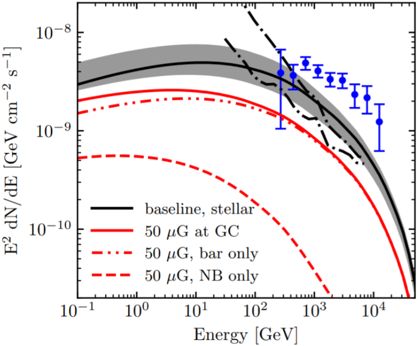


Main Result:

CTA is capable of distinguishing whether the inverse Compton signal emanates from dark matter or MSPs based on the spatial morphology of the radiating source.

Limits by H.E.S.S. measurements of the Galactic ridge.





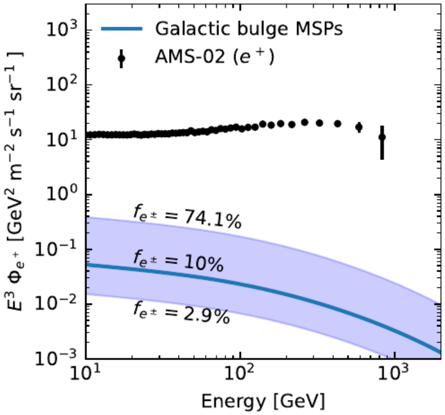
Predictions at the Galactic ridge:

- Assume $f_{e^\pm} = 10\%$.
- Assume $B = 10; \mu$G at the GC.
- See Song et al. (2019).

Impact of the magnetic field:

- Assume $B = 50; \mu$G in the nuclear bulge .
- Contribution of the nuclear bulge drastically reduced, while not for the boxy bulge.

Implications for local CR measurements



Predicted $e^{\pm}$ fluxes at Earth:

- Even for very high $f_{e^\pm}$ values, the $e^{\pm}$ accelerated by Galactic bulge MSPs are not expected to be observed by local CR detectors.